5th Joint US-European Fluids Engineering Division Summer Meeting, July 15-20, 2018

Validation Of A CFD Model Predicting The Effect Of High Level Lateral Acceleration Sloshing On The Heat Transfer And Pressure Drop In A Small-scale Tank In Normal Gravity

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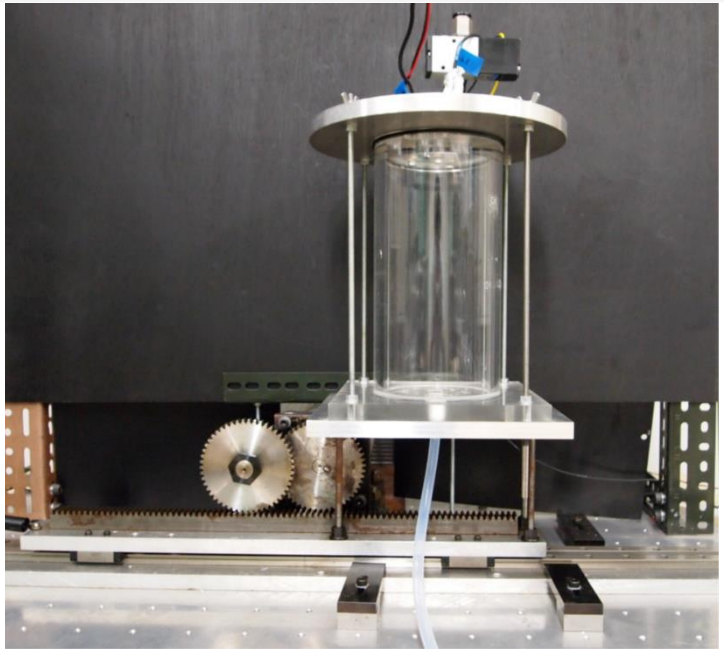
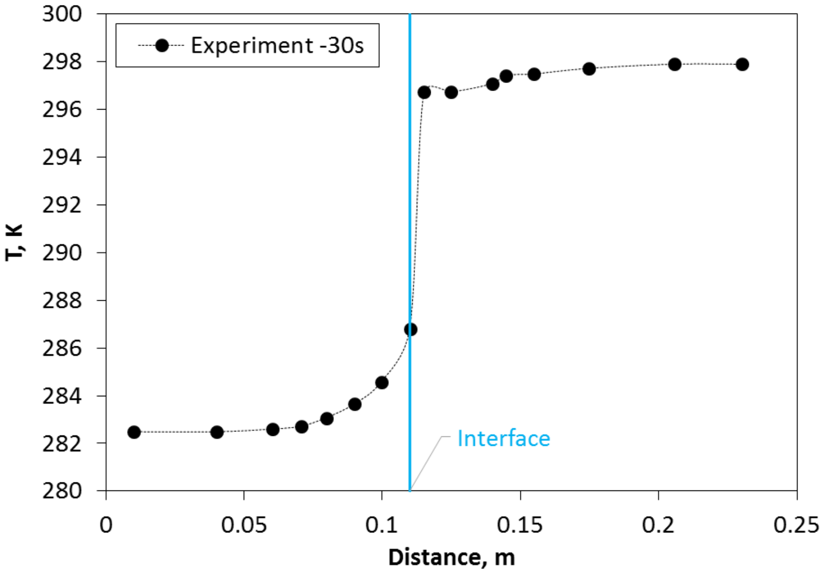
Overview

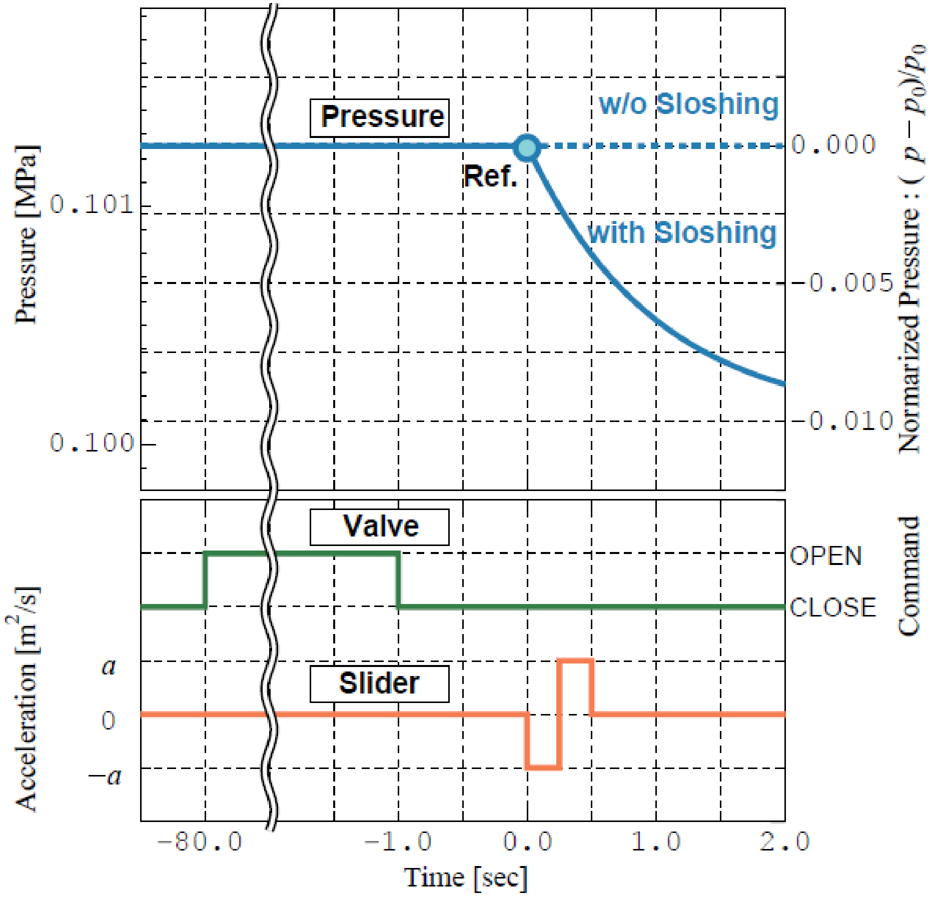
- Description of experiment
- CFD Results
    - Lateral acceleration 0.5 G
        - Cases without the tank wall (adiabatic)
        - Cases with the tank wall
    - Lateral acceleration 0.2 G
        - Cases with the tank wall
- Conclusions

Experimental setup and procedure

- Experiment conducted by Himeno at al. (AIAA2011-5682); CFD modeling performed under NASA-JAXA collaboration
- Silicone oil KF96L-1cSt and Air
- Tank inner diameter 0.110 m; height 0.230 m
- Tested lateral acceleration levels: 0.2G, 0.3G, 0.4G and 0.5 G
- 1 G
- One fluid temperature profile at -30 seconds prior to sloshing was provided, when conditions can change between the test points







Fluid and Wall Properties

- Some fluid properties for silicone oil (KF96L-1cSt) were provided by JAXA, the rest found online:

Fluid Properties:

Property	Units	Silicone Oil	Air
Density	kg/m^3	818	Ideal gas
C_p	J/kg-K	2000	1006.43
Thermal Conductivity	W/m-K	0.1	0.0242
Viscosity	kg/m-s	0.000818	1.7894e-05
Surface Tension	N/m	0.0169	
Thermal Expansion coeff.	1/K	0.00129	
Molecular Weight	Kg/kmol	74	28.966

Wall Properties (acrylic):

Property	Units	Acrylic
Density	kg/m^3	1170
C_p	J/kg-K	1466
Thermal Conductivity	W/m-K	0.21

https://www.shinetsusilicone-global.com/catalog/pdf/kf96_e.pdf

Computational Model: Equations Solved

Continuity: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m$$

Momentum: $$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F}\ ,$$

where stress tensor is: $$\bar{\bar{\tau}} = \mu \left[(\nabla \vec{v} + \nabla \vec{v}^{\mathrm{T}}) - \frac{2}{3} \nabla \cdot \vec{v} I \right]$$

Energy: $$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \big(\vec{v}(\rho E + p)\big) = \nabla \cdot \left(k_{\mathrm{eff}} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\bar{\tau}}_{\mathrm{eff}} \cdot \vec{v}) \right) + S_h$$

Volume of Fluid (VOF) model:

Energy and Temperature are defined as mass average scalars: $$E = \frac{\sum_{q=1}^{2} \alpha_q \rho_q E_q}{\sum_{q=1}^{2} \alpha_q \rho_q}$$

Properties: $$\rho = \sum_{q=1}^{2} \alpha_q \rho_q,\ \ \mu_{eff} = \sum_{q=1}^{2} \alpha_q \mu_{eff\ q},\ \ k_{eff} = \sum_{q=1}^{2} \alpha_q k_{eff\ q}$$

Continuity of Volume Fraction of the *q*-th phase: $$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = S_{\alpha_q} \right]$$

Continuum Surface Force (Brackbill et al.): $$F_{vol} = \sum_{\text{pairs } ij,\ i<j} \sigma_{ij} \frac{\alpha_i \rho_i h_j \nabla \alpha_j + \alpha_j \rho_j h_i \nabla \alpha_i}{\frac{1}{2}(\rho_i + \rho_j)}$$

where $h_i = \nabla \cdot \hat{n}$

Computational Model: Numerical Methods

- Simulations performed using ANSYS Fluent version 17
- **3D** geometry was modeled
- Compressible ideal gas
- Surface tension effects via Continuum Surface Force method of Brackbill et al.

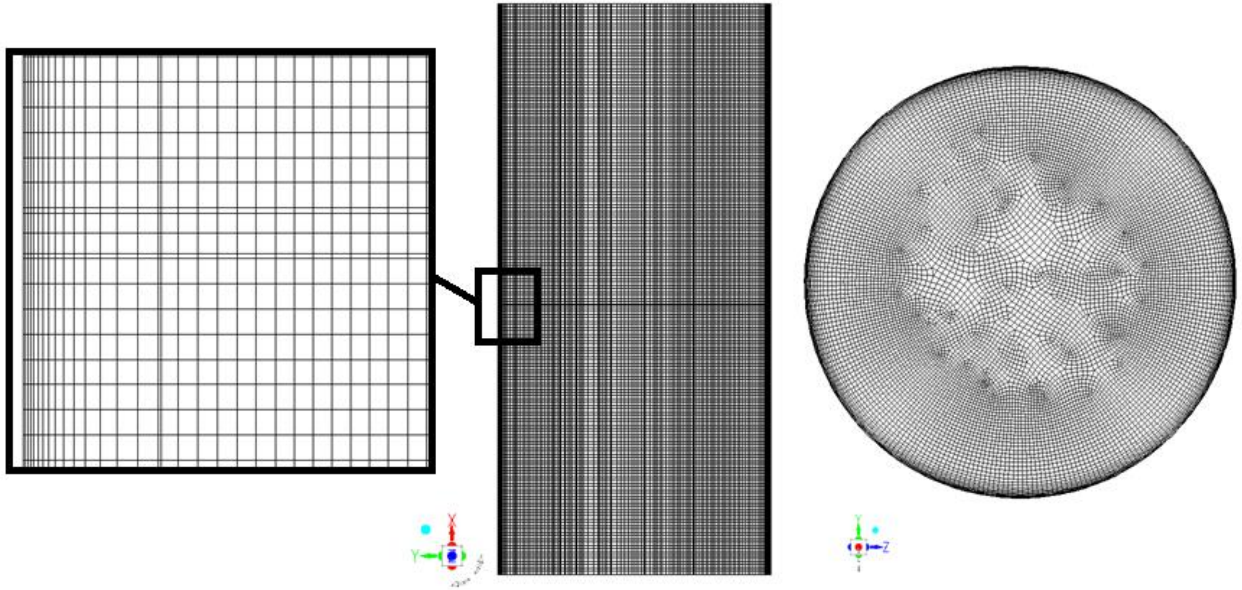
RANS

- Second Order Upwind scheme was used for discretization of the Energy, Momentum and Turbulence equations (cell values)
- PISO scheme was used for the Pressure-Velocity coupling (cell values)
- Least Squares Cell Based scheme was used for the gradient calculations (face values)
- Body Force Weighted scheme was used for the Pressure interpolation (face values)
- Point Implicit (Gauss-Seidel) linear equation solver with Algebraic Multi-Grid (AMG) method was used for solving linearized systems of equations
- First Order Implicit temporal discretization was used with explicit VOF model with Δt = 1e-4 s

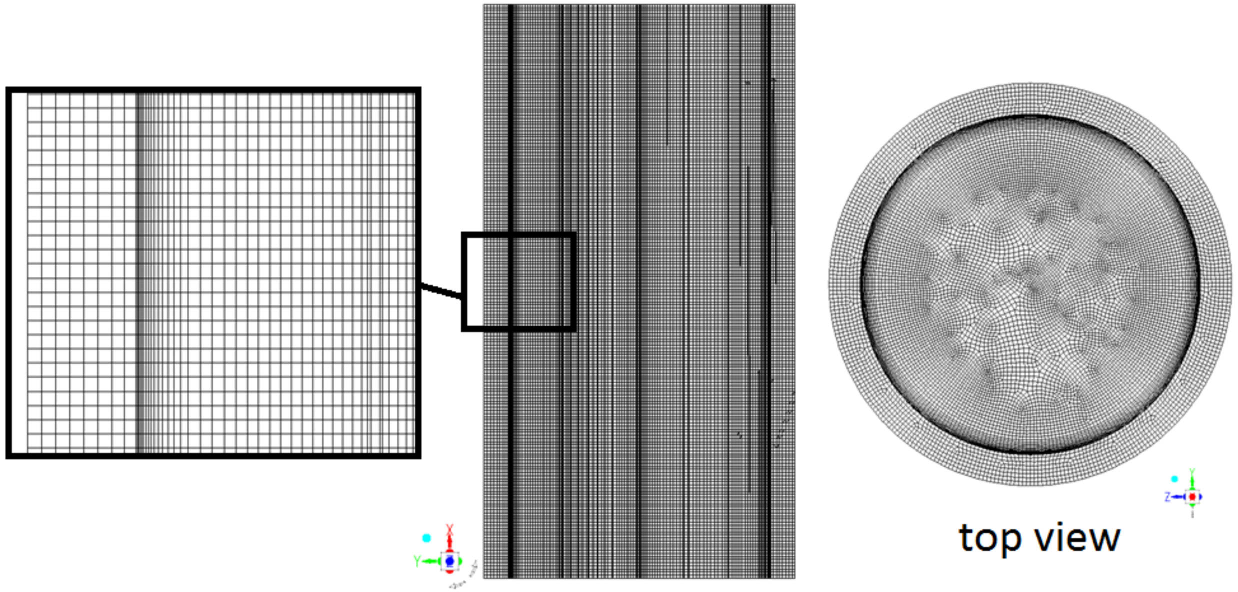
LES

- Bounded Central Differencing scheme was used for discretization of the Momentum equation (cell values)
- Second Order Upwind scheme was used for discretization of the Energy equation (cell values)
- PISO scheme was used for the Pressure-Velocity coupling (cell values)
- Least Squares Cell Based scheme was used for the gradient calculations (face values)
- Body Force Weighted scheme was used for the Pressure interpolation (face values)
- Point Implicit (Gauss-Seidel) linear equation solver with Algebraic Multi-Grid (AMG) method was used for solving linearized systems of equations
- Bounded Second Order Implicit temporal discretization was used with explicit VOF model with Δt = 5e-5 s

Computational Mesh: RANS



Front View　　　Top View

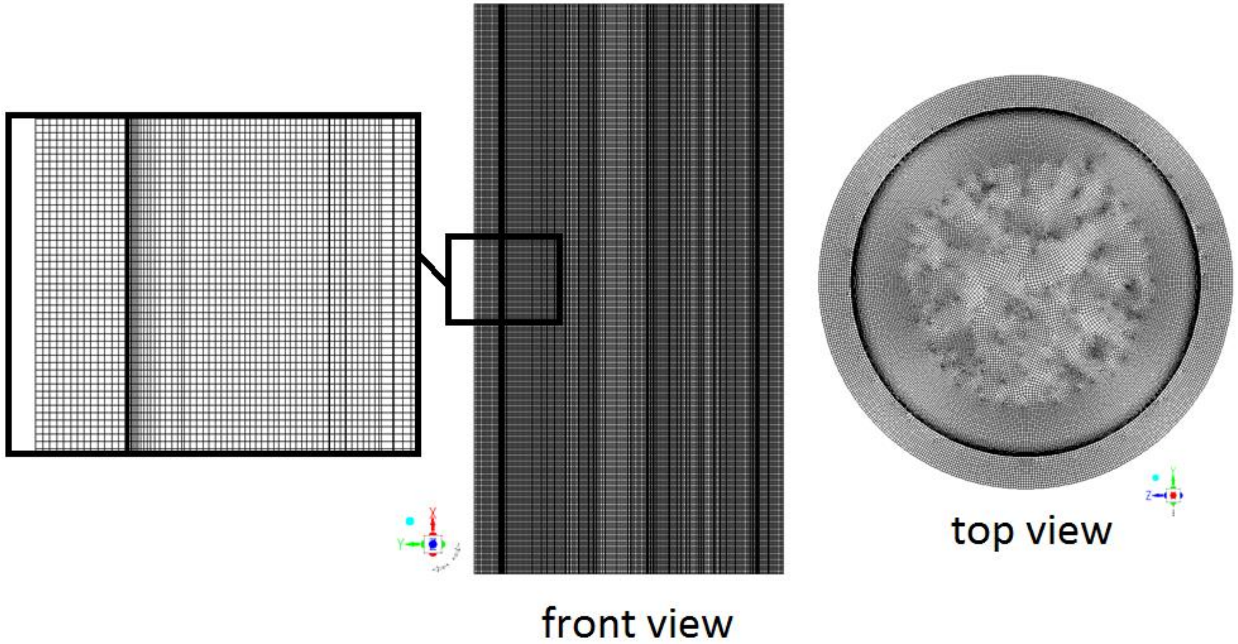


front view　　　top view

without the tank wall 2,059,200 cells

with the tank wall 2,573,165 cells

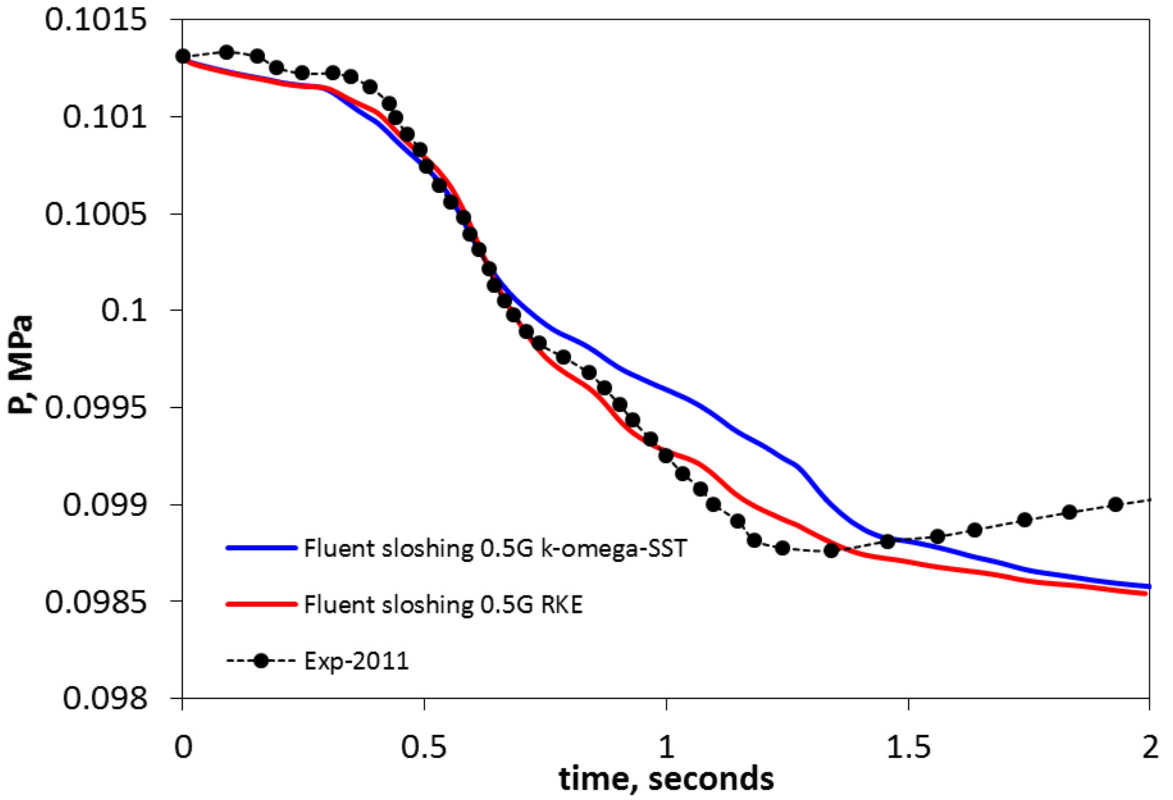
Computational Mesh: LES



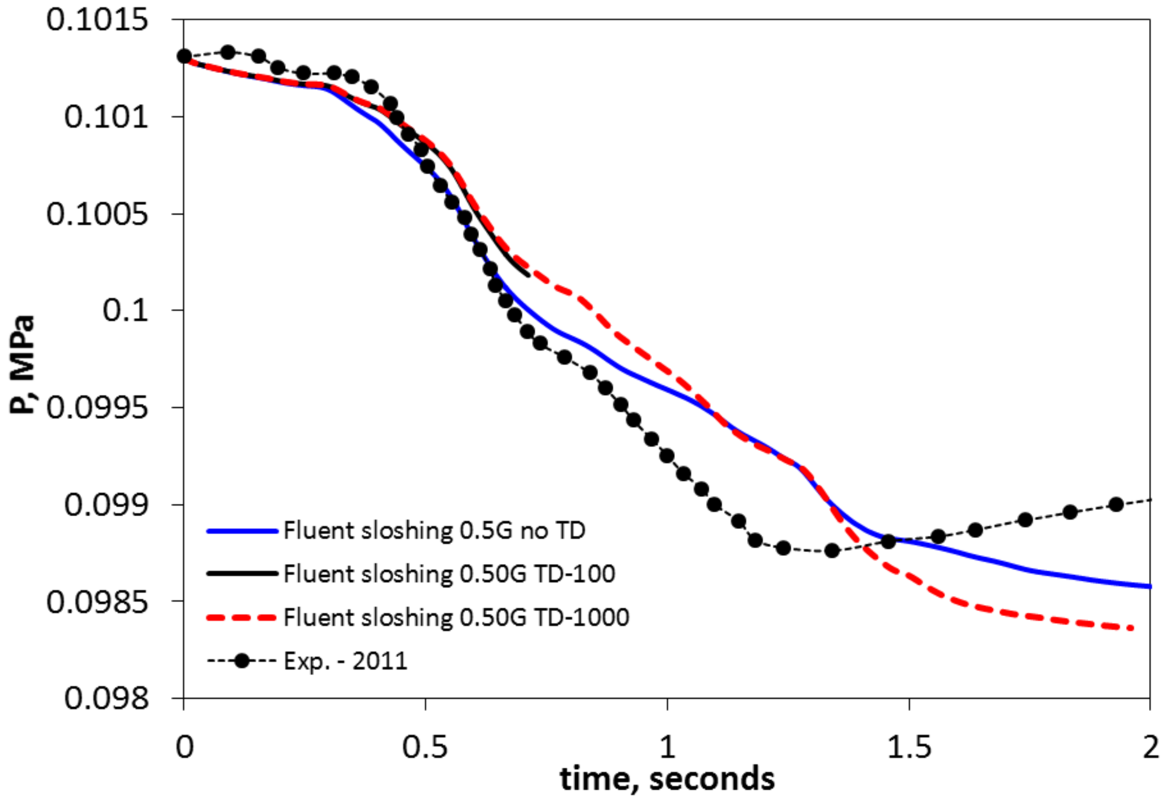
with the tank wall used in the LES case (9,576,315)

CFD Results: High Lateral Acceleration (0.5 G)

Results of the cases without the tank wall: 0.5G



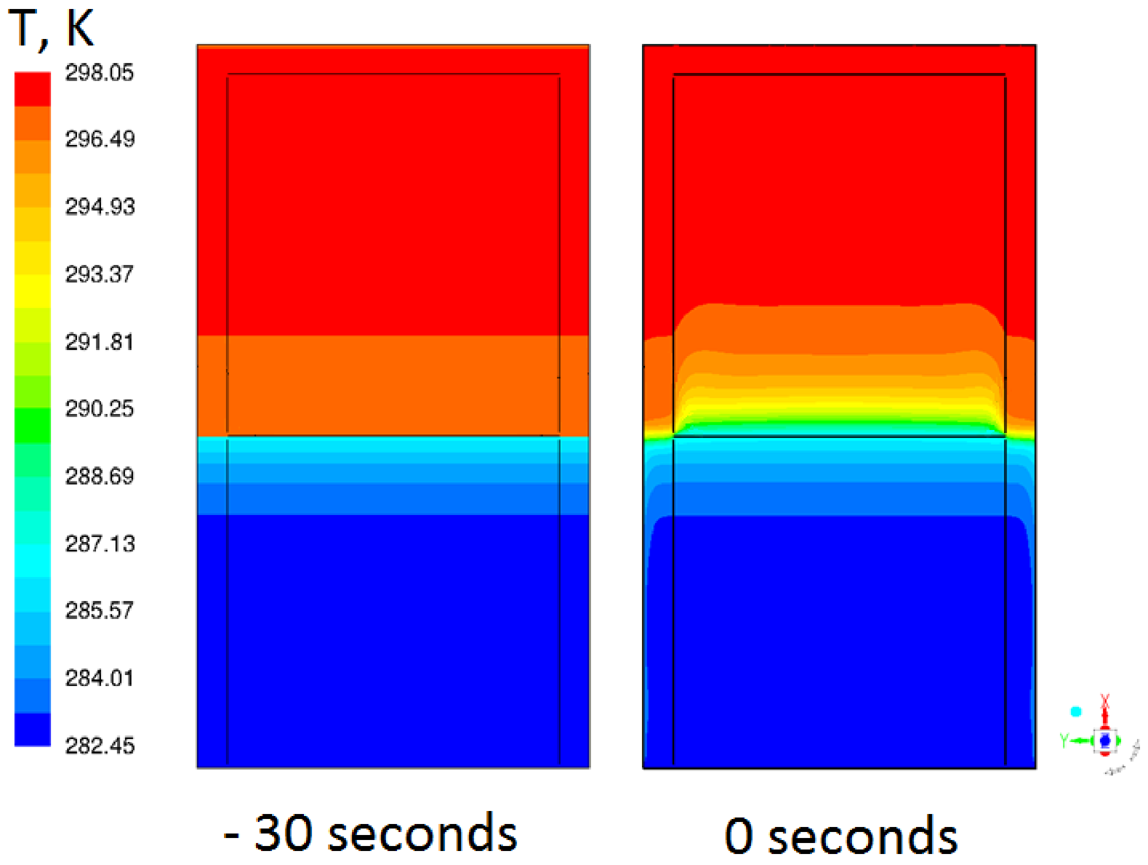
Effect of turbulence model



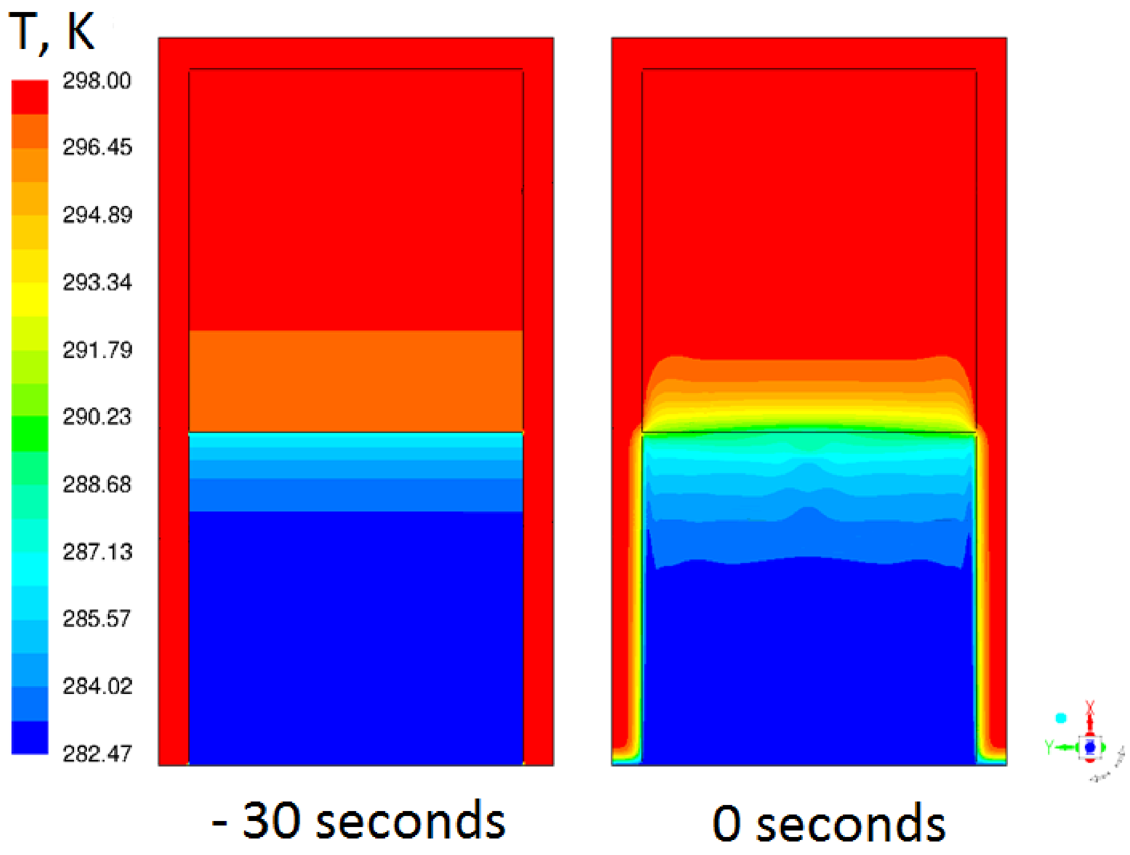
Effect of turbulence damping at the interface

Results of the cases with the tank wall: 0.5G

Obtaining Initial Conditions: Sharp Interface Model

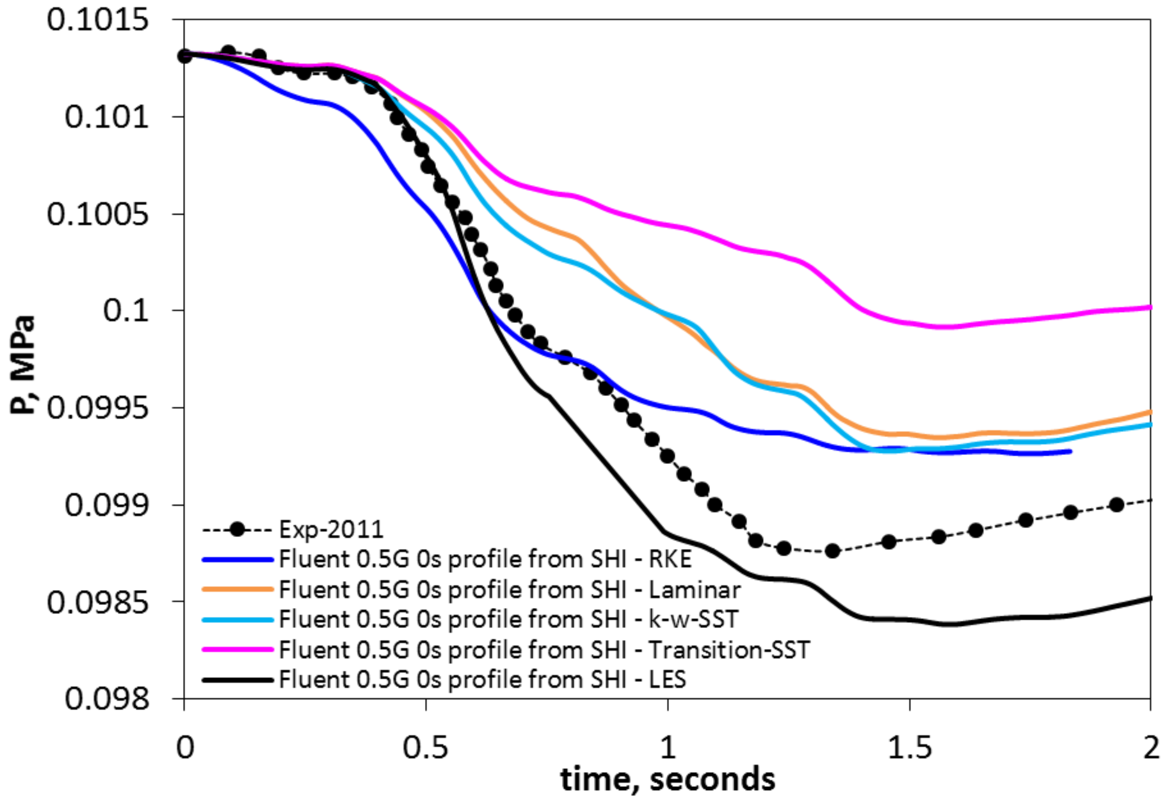


Matching Wall

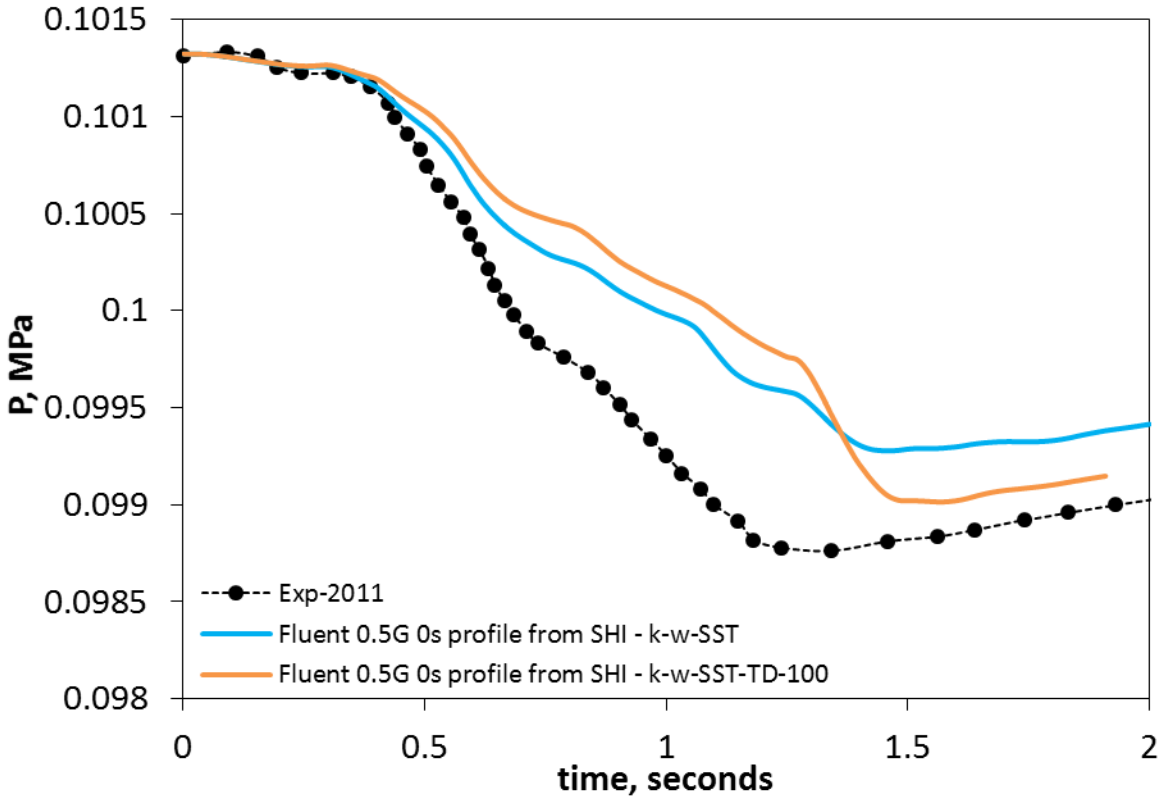


Hot Wall

Results of the cases with the tank wall: 0.5G

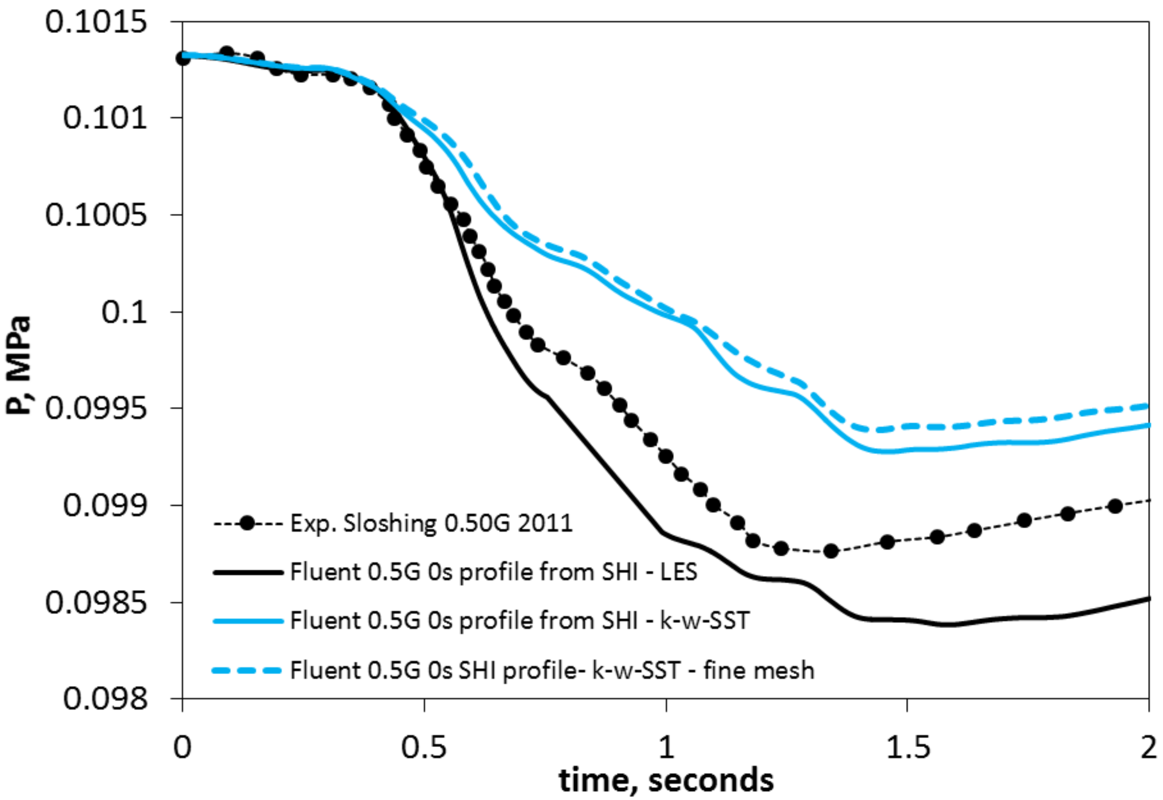


Effect of turbulence model



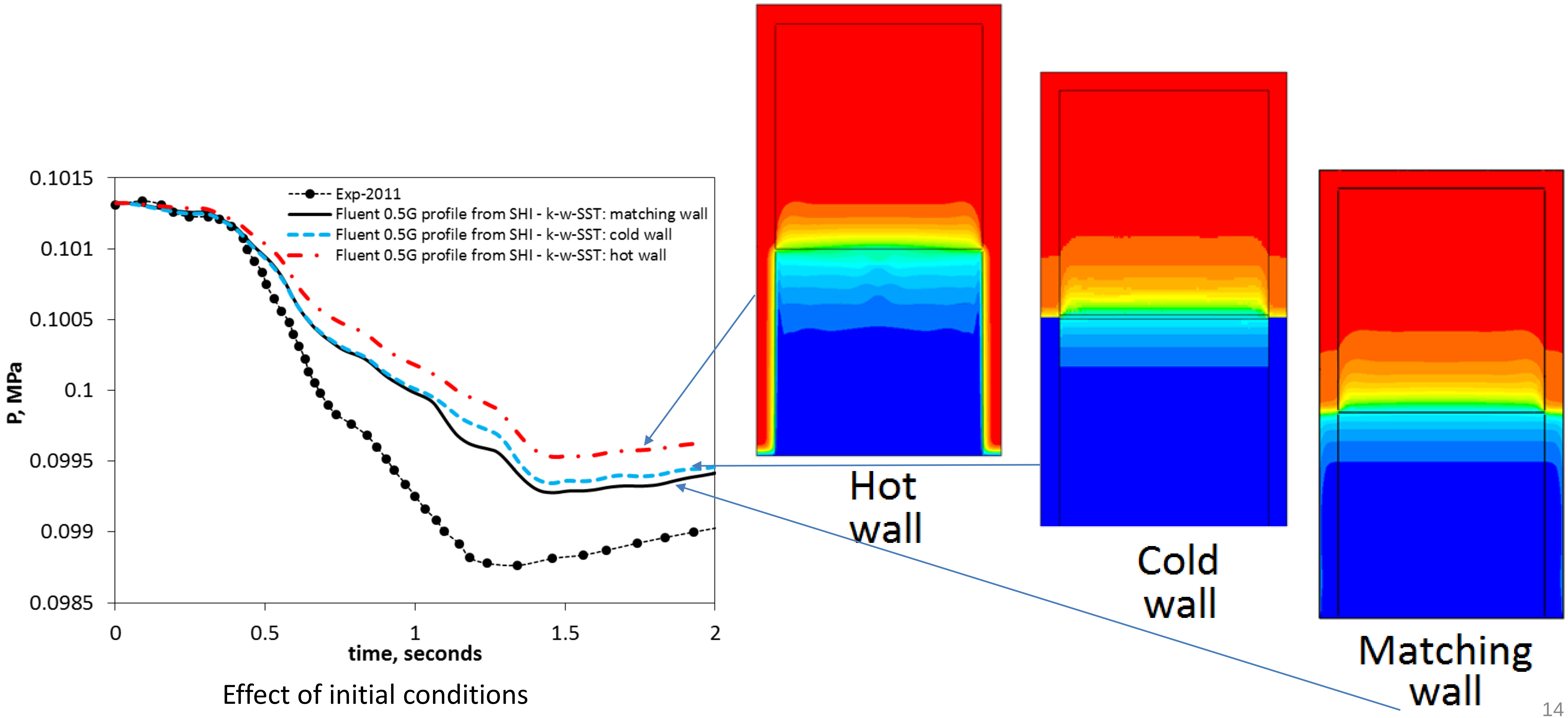
Effect of turbulence damping at the interface

Results of the cases with the tank wall: 0.5G



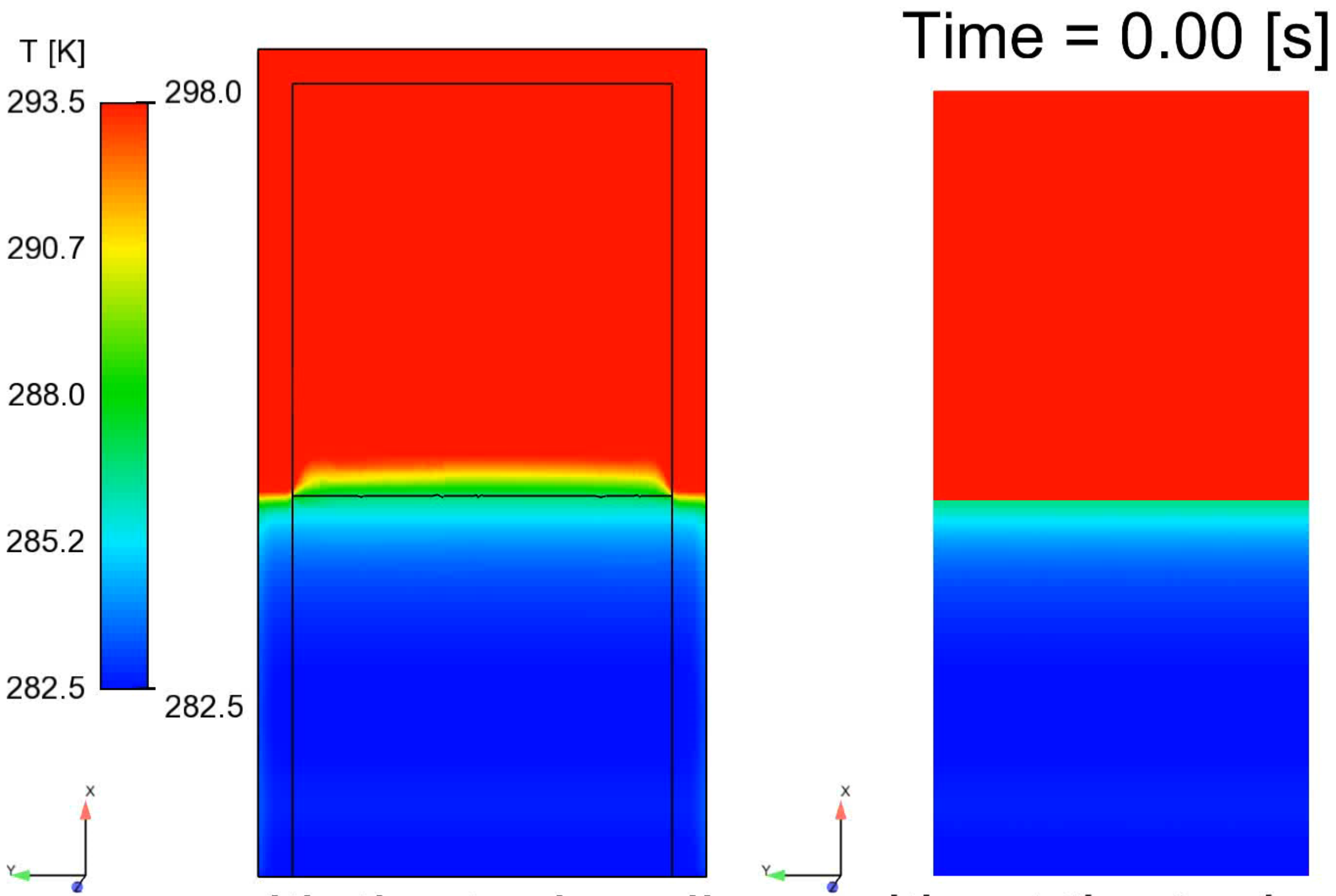
Effect of mesh size for RANS

Results of the cases with the tank wall: 0.5G



Effect of initial conditions

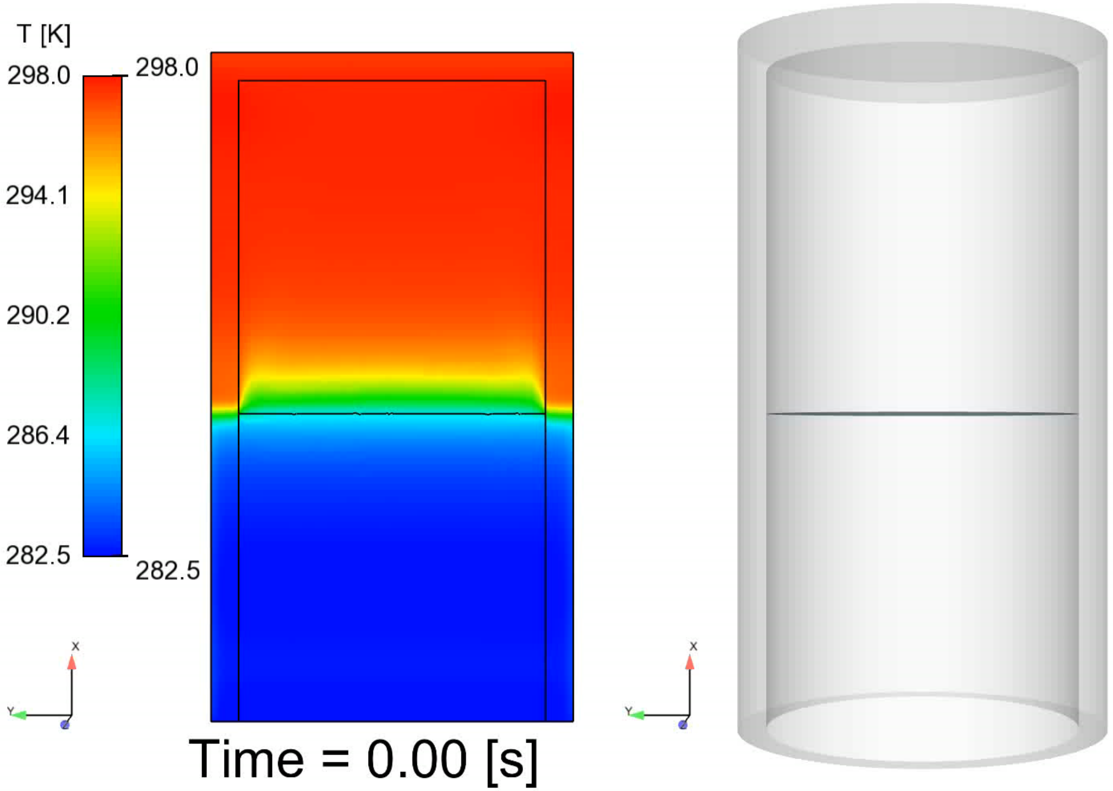
Case comparison with and without tank wall: 0.5G



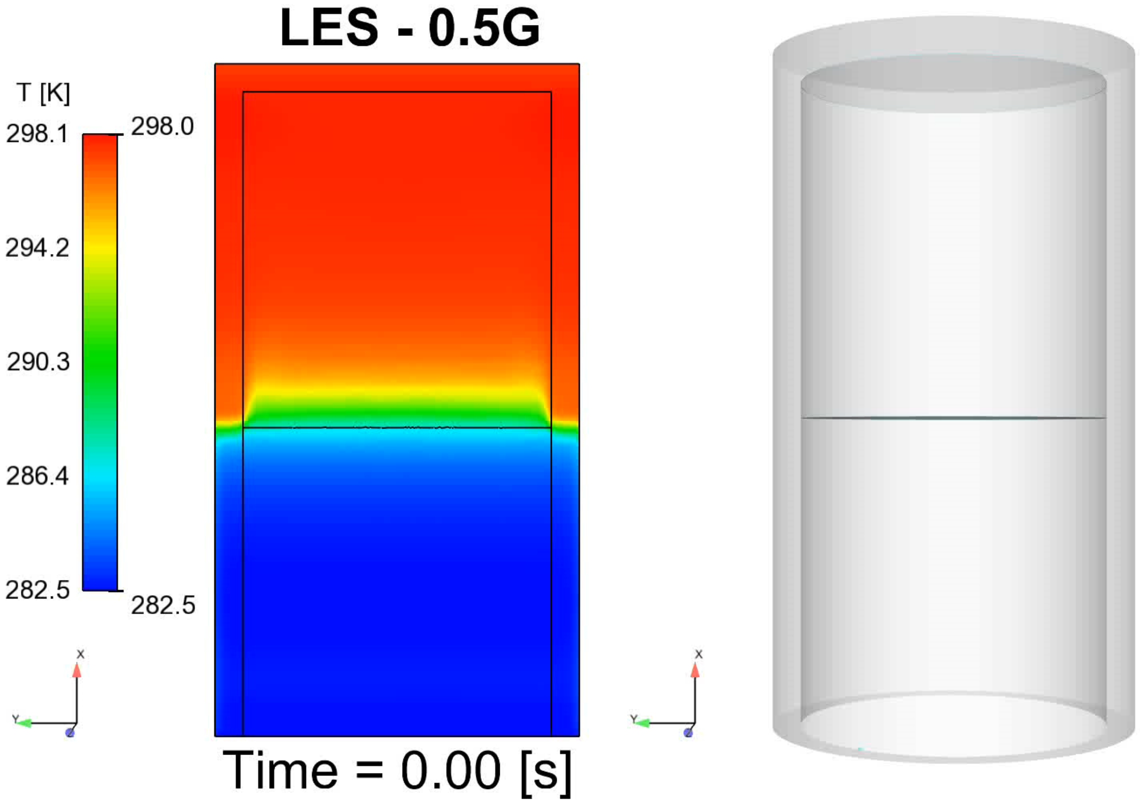
with the tank wall

without the tank wall

Case comparison LES vs. RANS: 0.5G



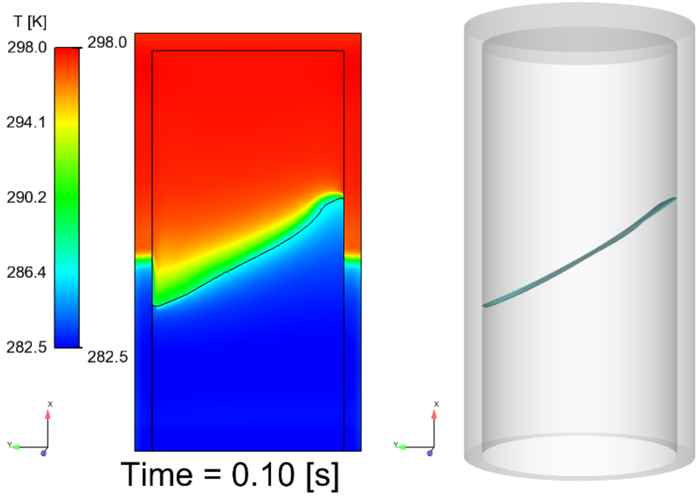
k-ω-SST



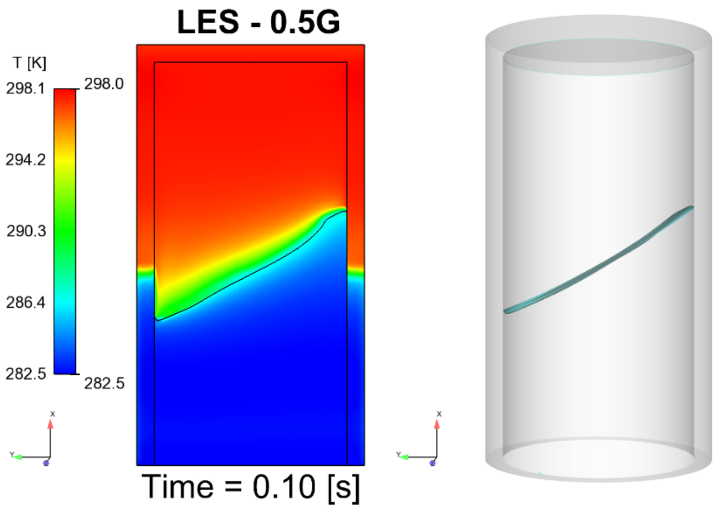
LES

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

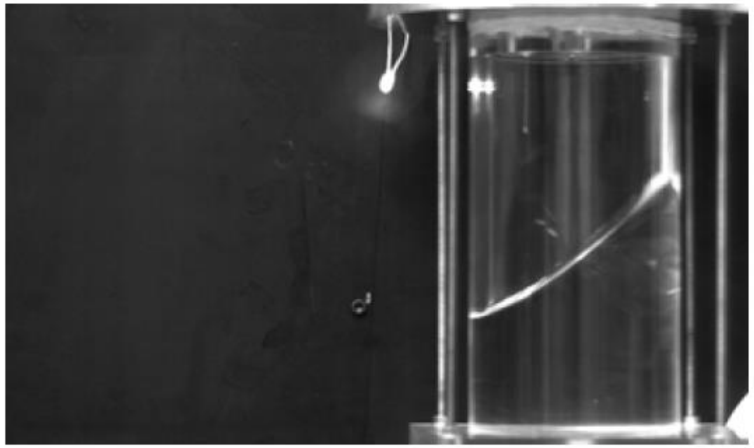
0.1 s



Fluent RANS



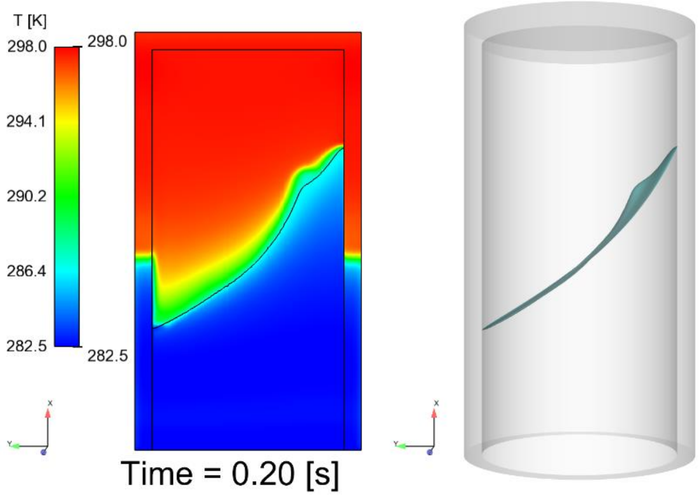
Fluent LES



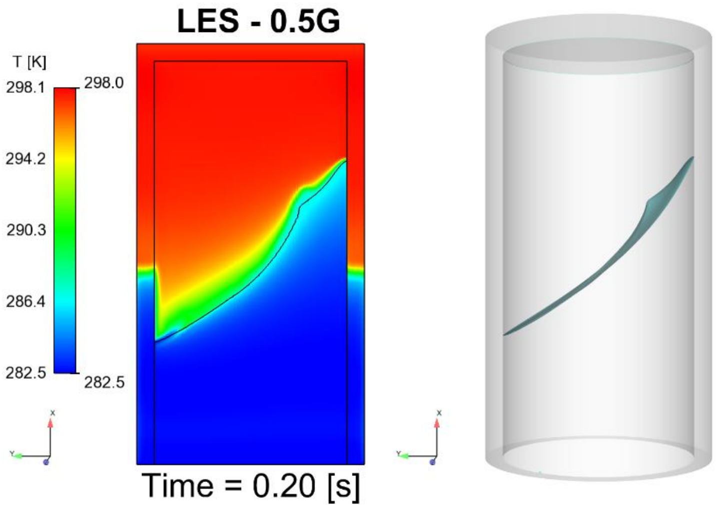
0.10 [sec]

Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

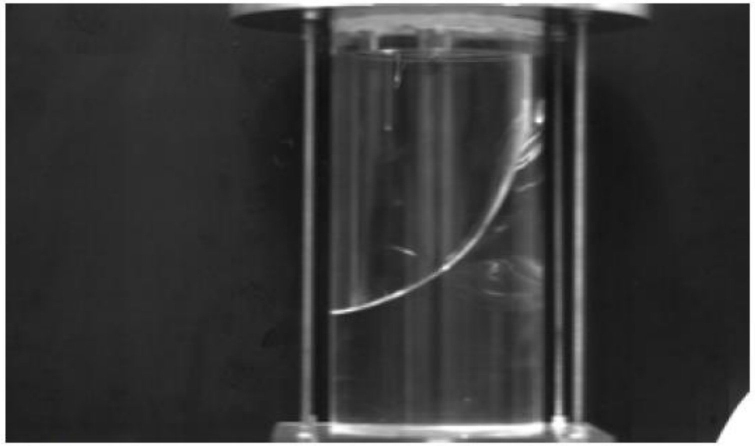


Fluent RANS



Fluent LES

0.2 s

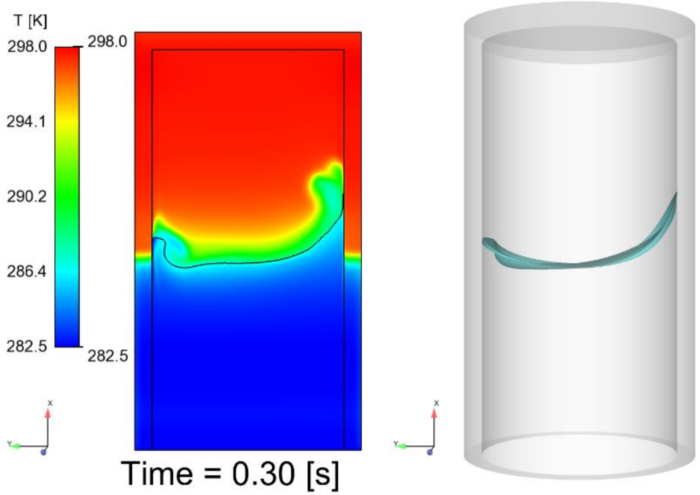


0.20 [sec]

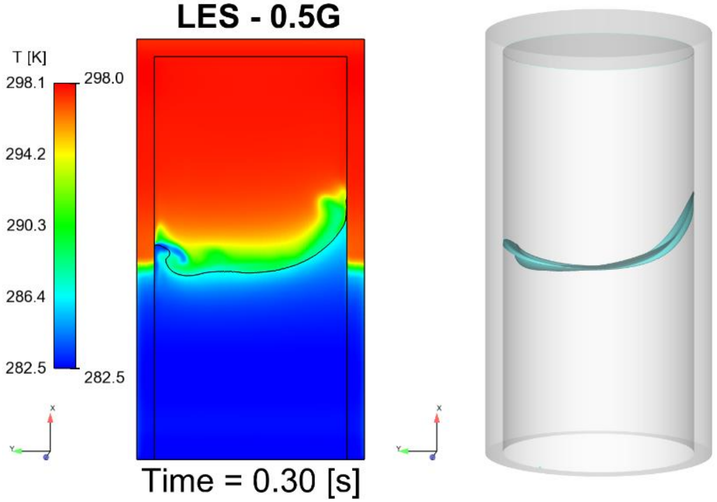
Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

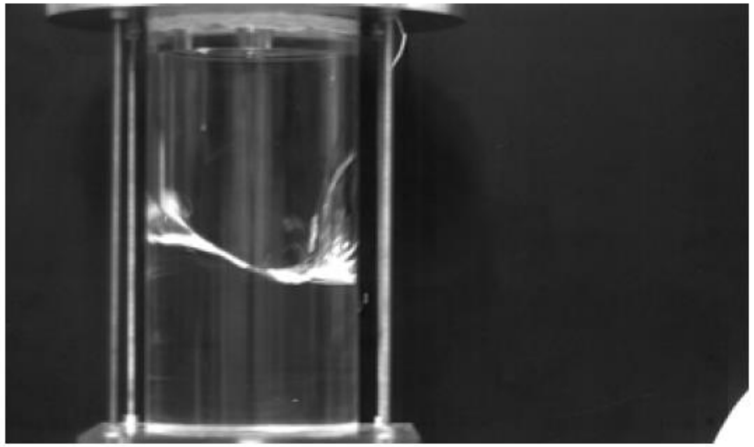
0.3 s



Fluent RANS



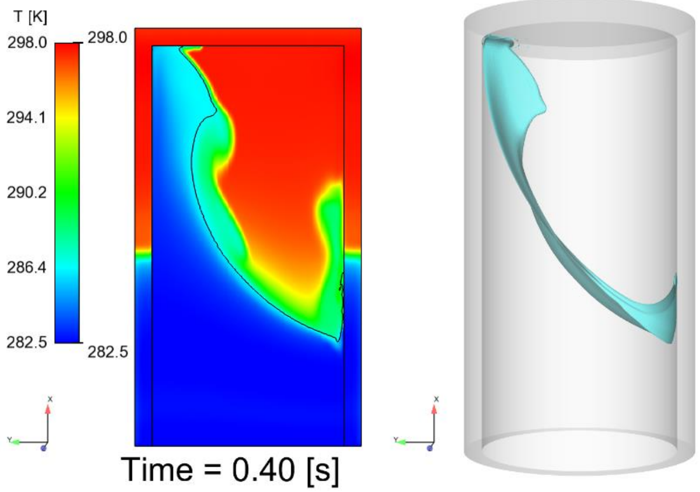
Fluent LES



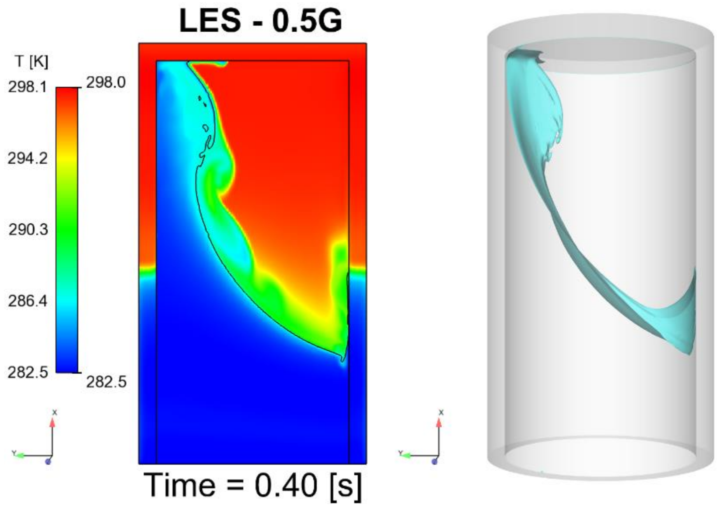
0.30 [sec]

Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

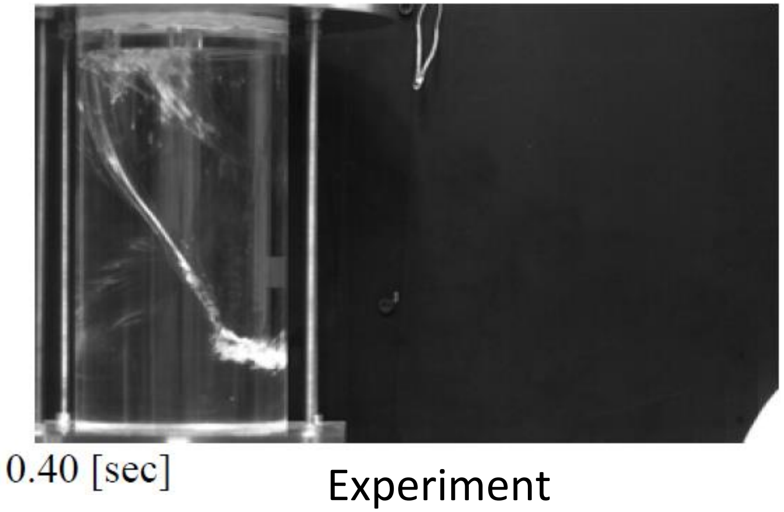


Fluent RANS



Fluent LES

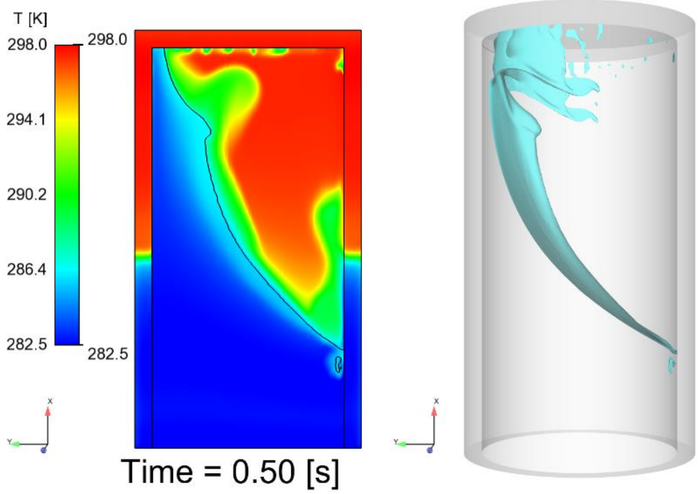
0.4 s



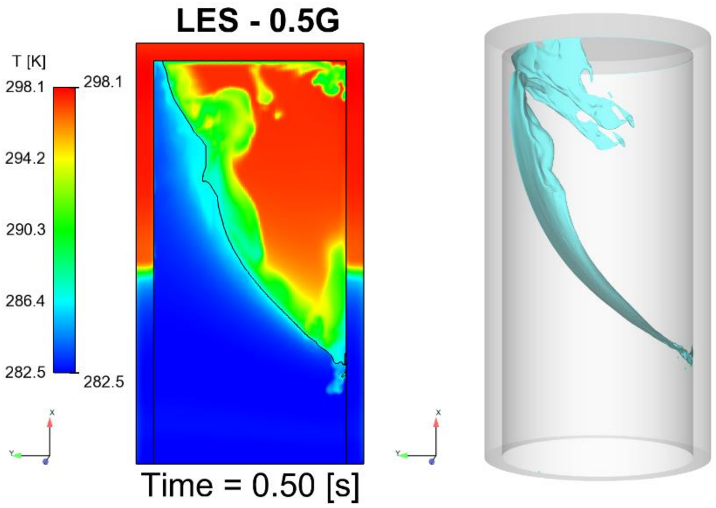
Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

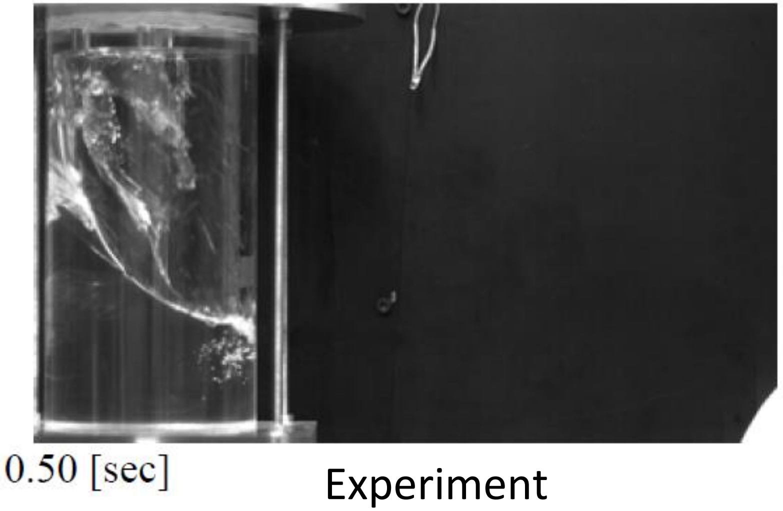
0.5 s



Fluent RANS



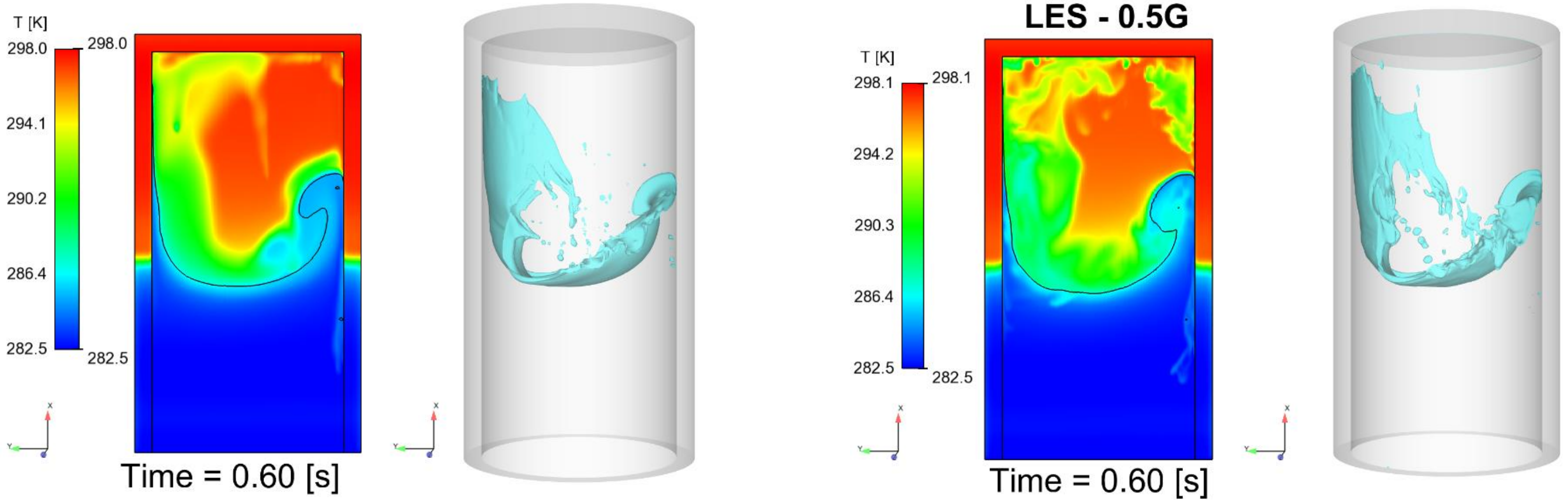
Fluent LES



Experiment

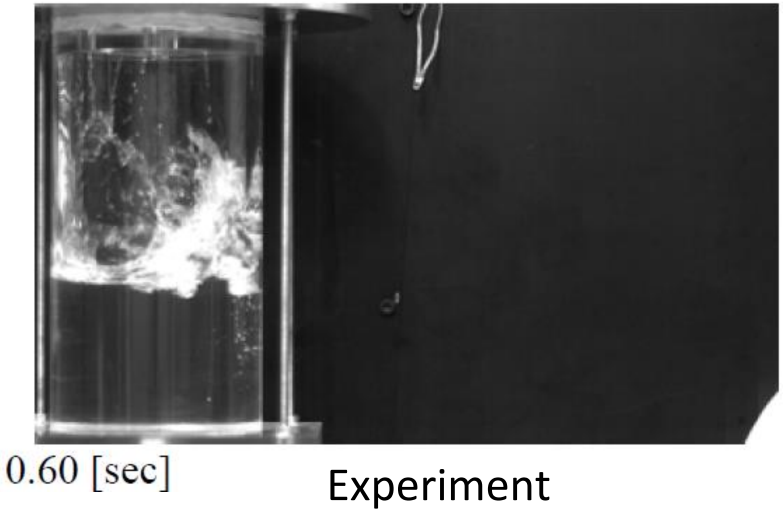
Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

0.6 s



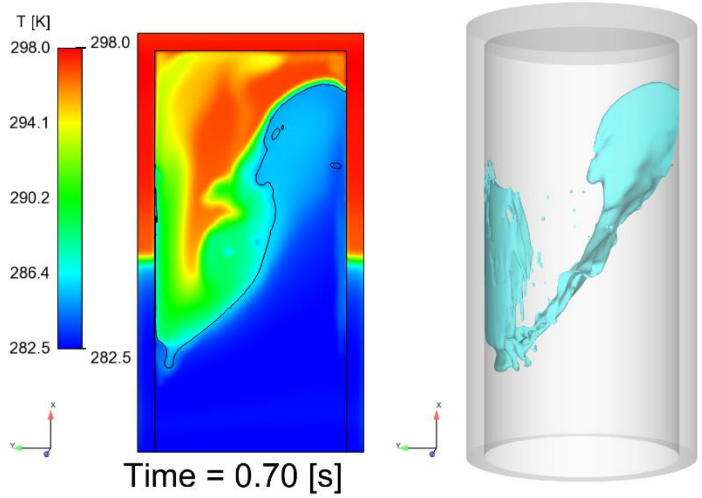
Fluent RANS

Fluent LES

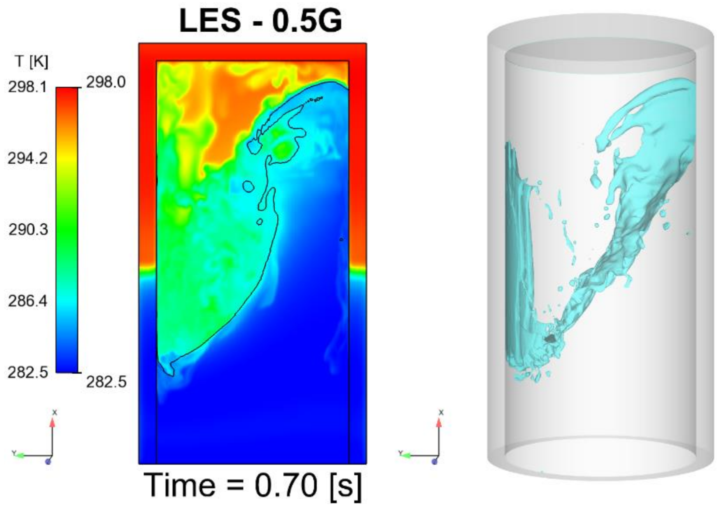


Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

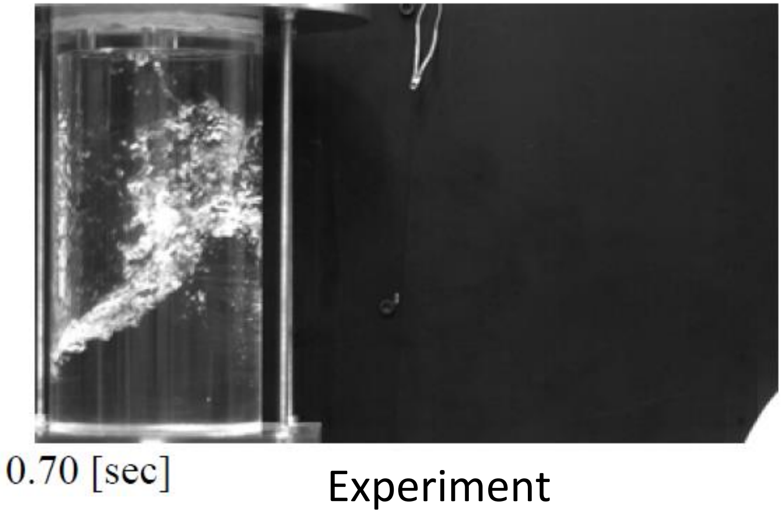


Fluent RANS



Fluent LES

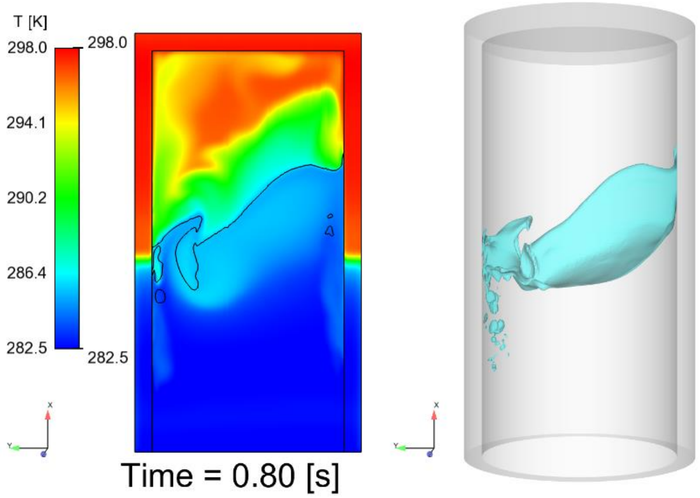
0.7 s



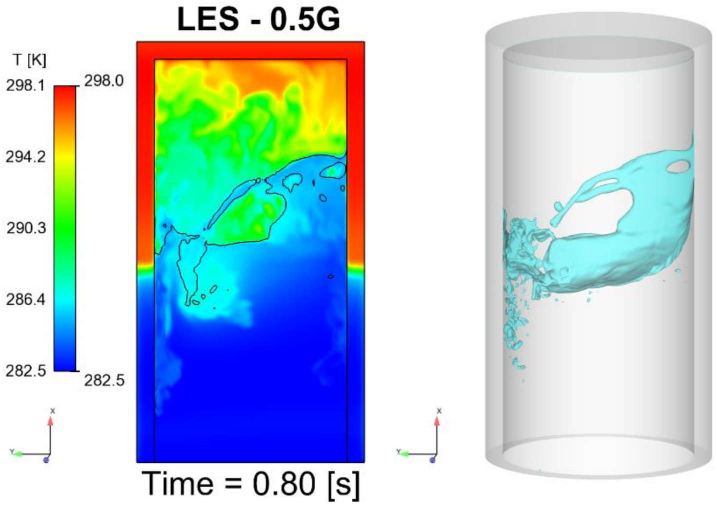
Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

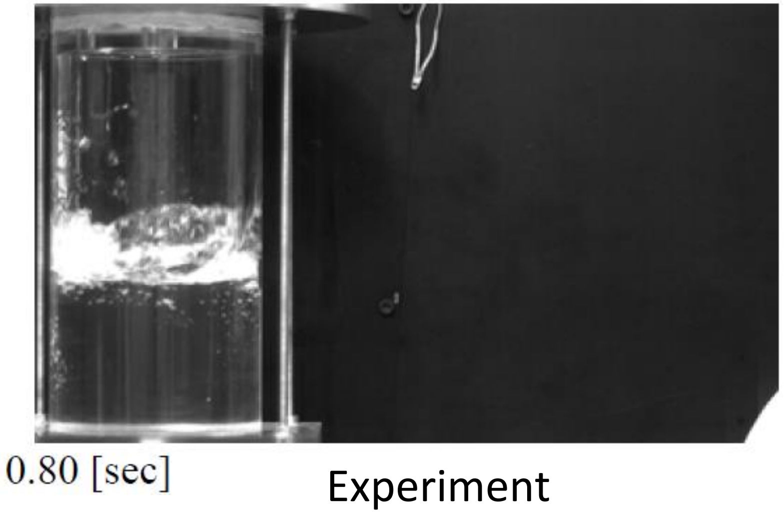
0.8 s



Fluent RANS

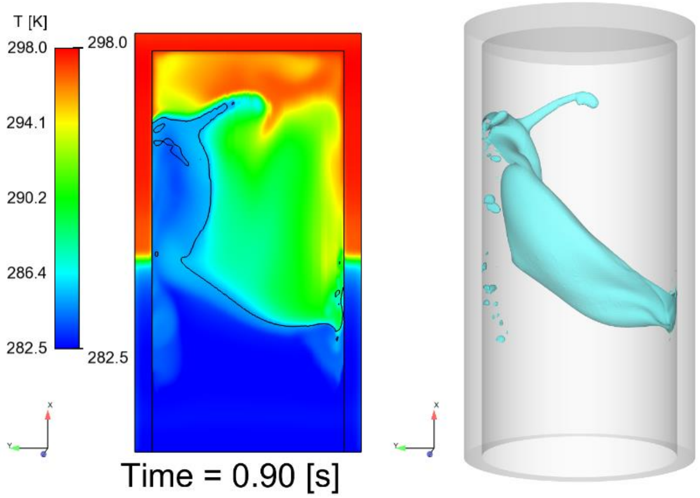


Fluent LES

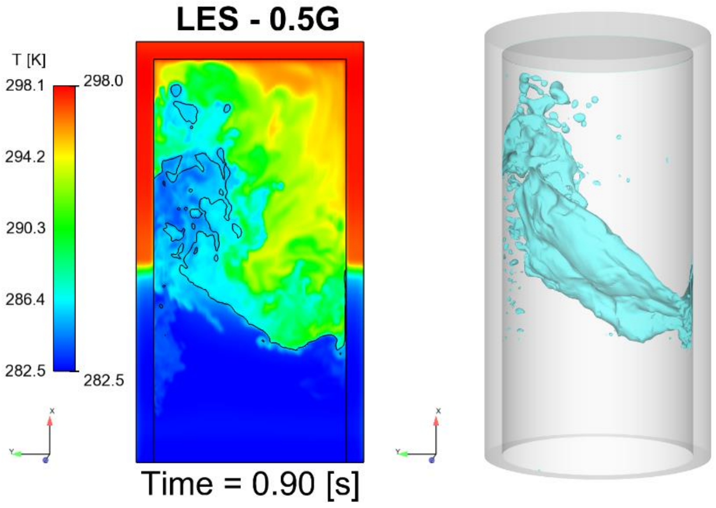


Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

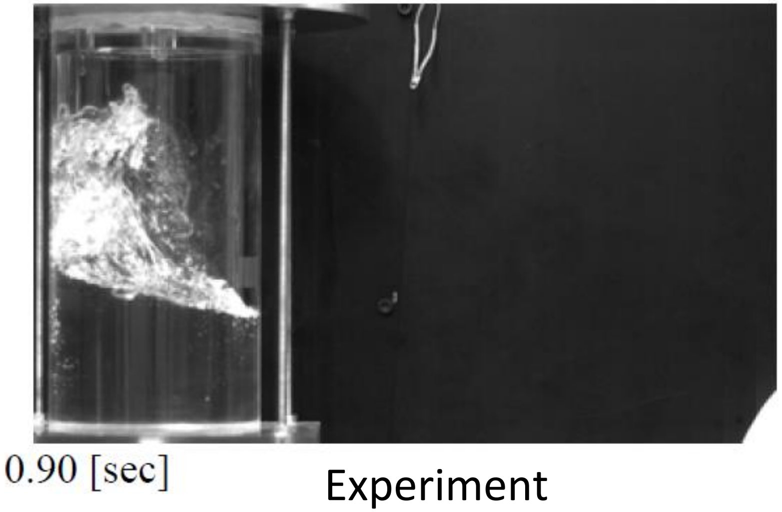


Fluent RANS



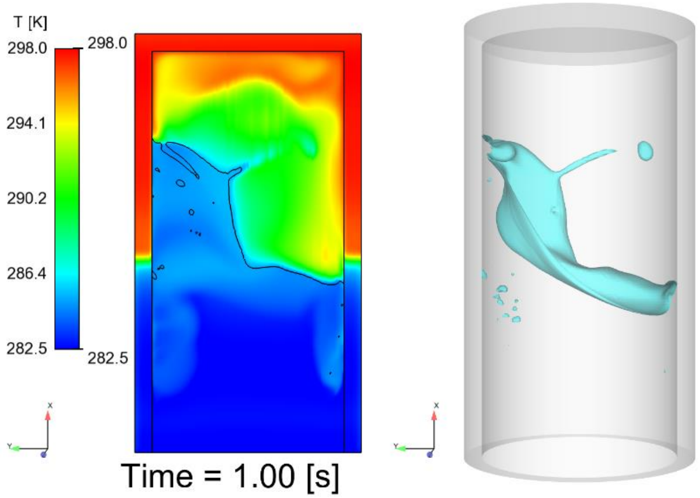
Fluent LES

0.9 s

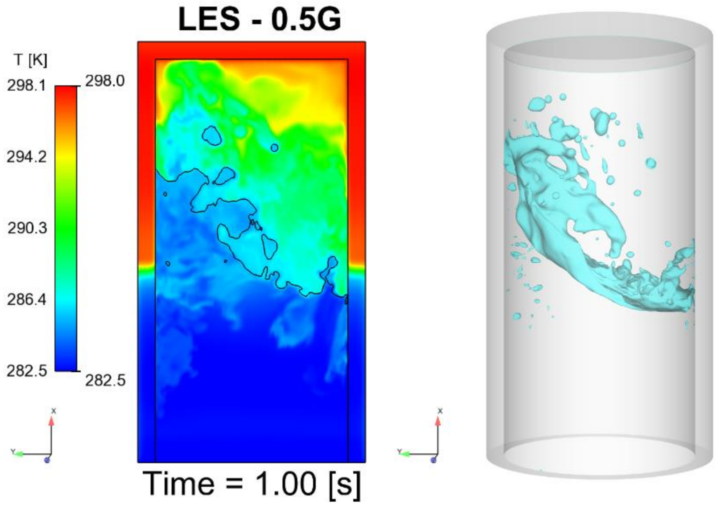


Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

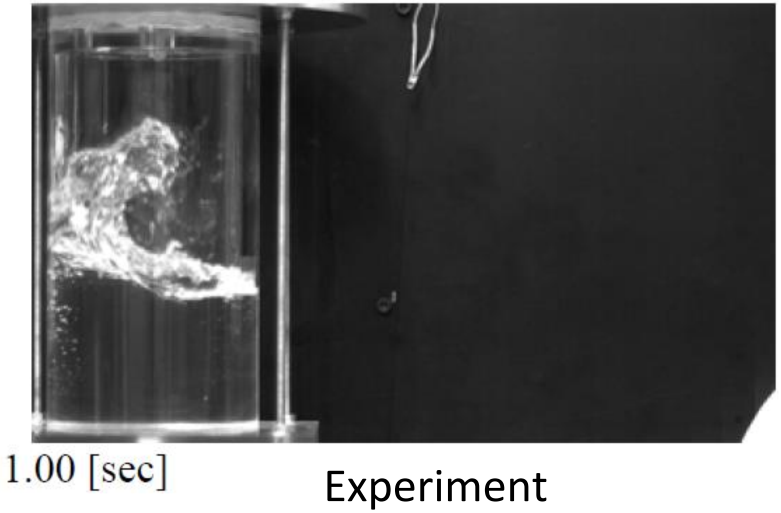


Fluent RANS



Fluent LES

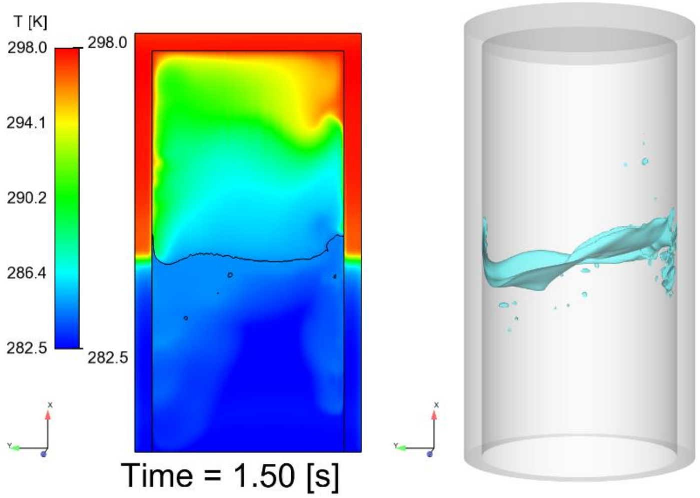
1.0 s



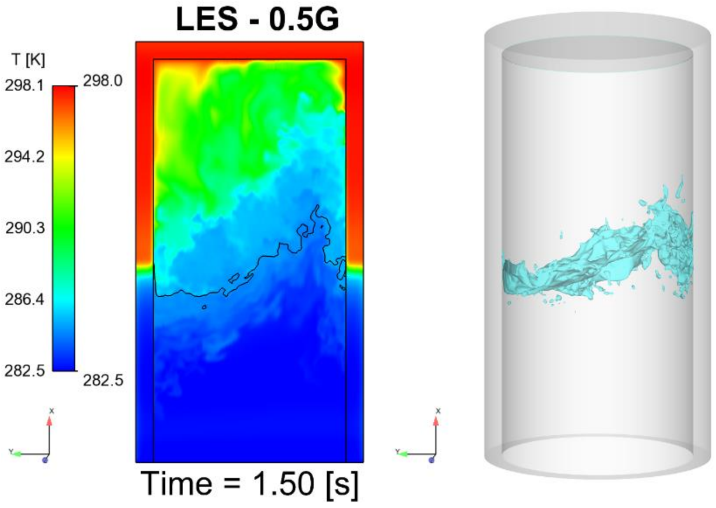
Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

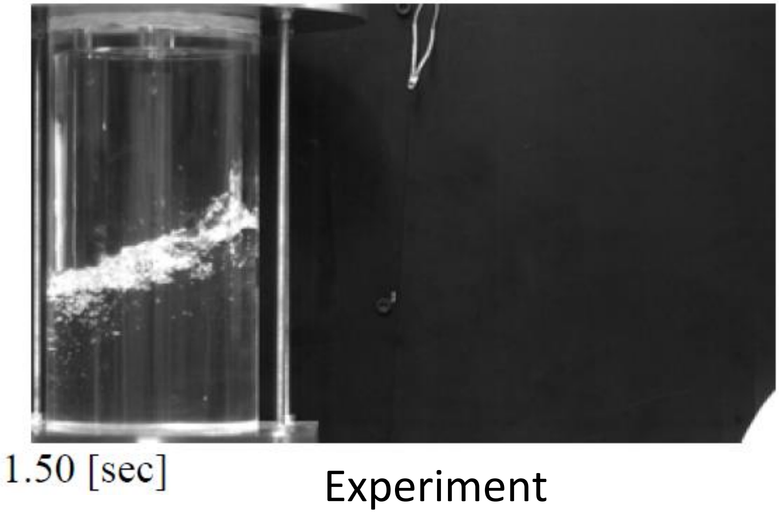
1.5 s



Fluent RANS



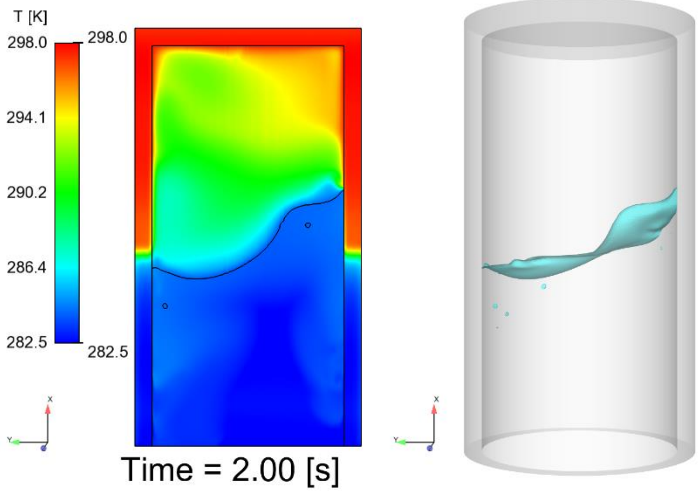
Fluent LES



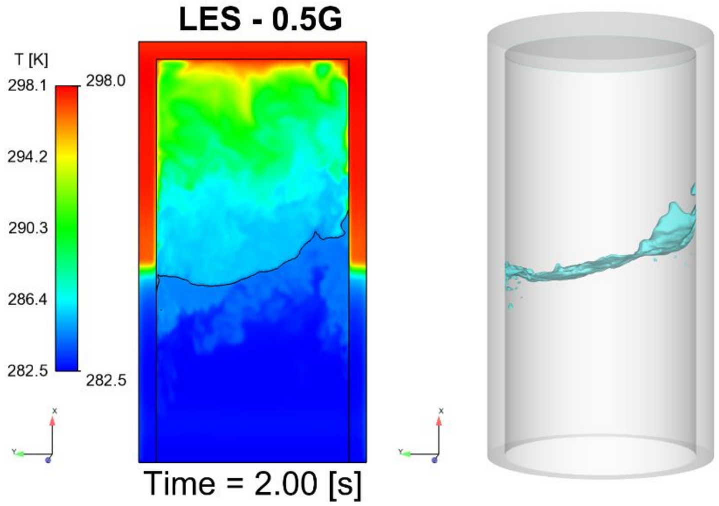
Experiment

Comparison between NASA Fluent LES, RANS and Experiment: 0.5G

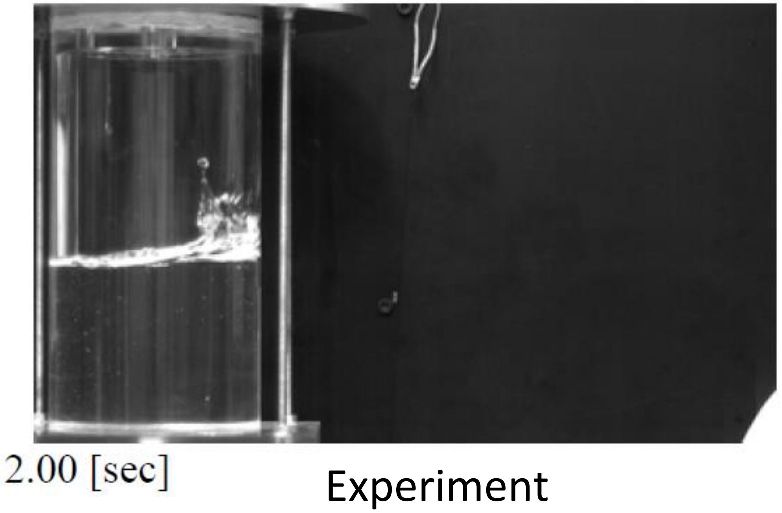
2.0 s



Fluent RANS



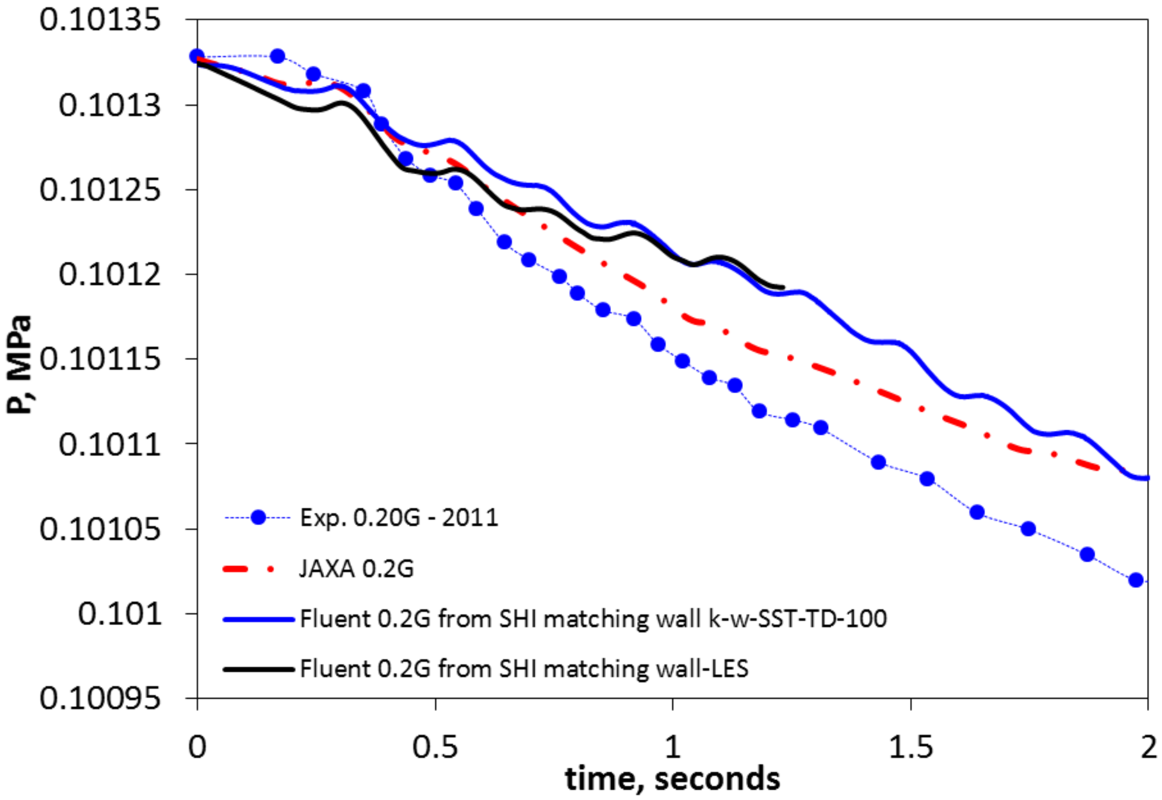
Fluent LES



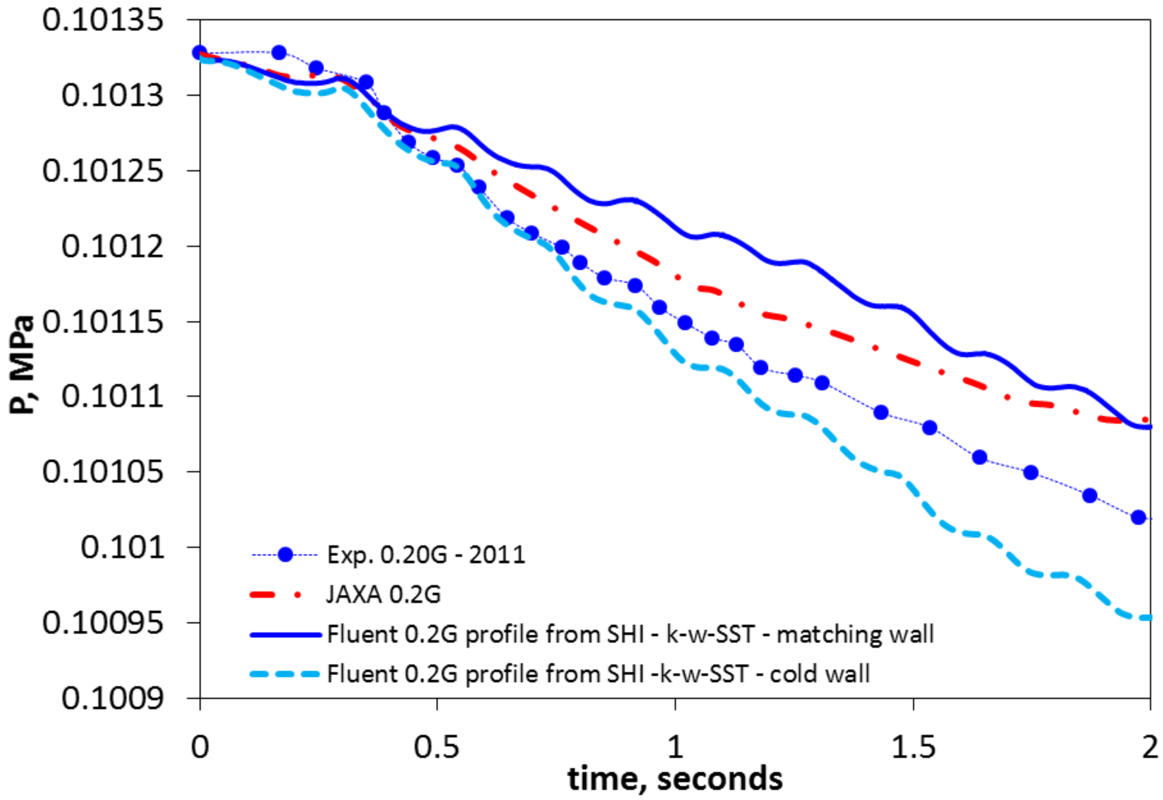
Experiment

CFD Results: Low Lateral Acceleration (0.2 G)

Results of the cases with the tank wall: 0.2G

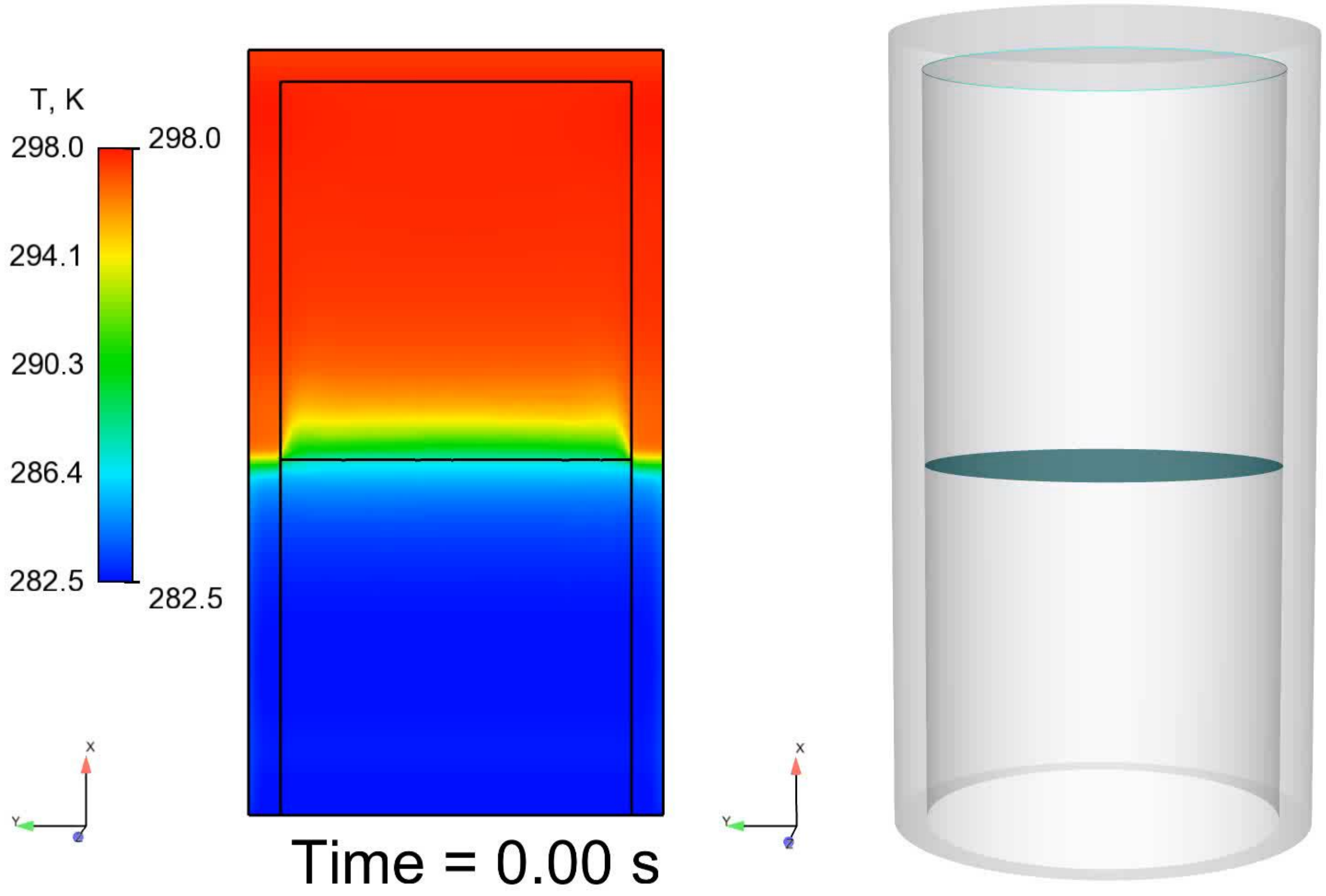


Effect of turbulence model



Effect of initial conditions

Results of the cases with the tank wall: 0.2G



Conclusions

- Silicone oil sloshing cases with 0.5G and 0.2G accelerations were simulated. Different factors affecting tank pressure during sloshing were studied, including:
  - turbulence modeling approach
  - turbulence damping at the interface
  - Initial conditions
  - boundary conditions

- The turbulence modeling approach had a more pronounced effect on the tank pressure in the higher acceleration case of 0.5G. With LES approach being the best in comparison with the experimental interface motion and tank pressure

- The initial temperature of the tank wall had a more pronounced effect on the tank pressure during sloshing in the lower acceleration case of 0.2G

- It is necessary to use realistic initial and boundary conditions for accurate modeling of fluid sloshing

- In the higher acceleration cases with turbulent breakup of the interface the more sophisticated approach to turbulence modeling, such as LES, produces better agreement with the experimental data